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Dahlgren, Virginia

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THE SUSCEPTIBILITY OF X-BAND POINT-CONTACT DIODES TO MICROWAVE RADIATION

by

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FOREWORD

This work was performed at the Naval Weapons Laboratory, Dahlgren, Virginia, under Naval Electronics Systems Command Task XF 53.533.002-E04.

This report was reviewed and approved by L. J. Lysher, Head, Electromagnetic Vulnerability Division.

Released by:

C. W. BERNARD, Head
Advanced Systems Department

ABSTRACT

This report describes the techniques and results of an investigation of the susceptibility of 1N23 point-contact microwave diodes to RF (9.375 GHz) energy. Using a minimum change in noise figure of 10 dB as the failure criterion, failure levels have been determined as a function of pulse width, pulse repetition frequency, and the number of pulses applied. The two significant results obtained are that the 50-percent failure level is independent of pulse repetition rate at least up to 10 KHz and an empirical expression is derived which predicts these failure levels. This expression is proportional to the log of the pulse width times the number of pulses applied. Utilization of the data is demonstrated by analysis of the susceptibility of a hypothetical system under an RF stress condition.

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I. INTRODUCTION

This report describes the techniques and results of an investigation of the susceptibility of 1N23 microwave mixer diodes to X-band radio-frequency (RF) radiation. Approximately 1000 diodes were subject to RF (9.375 GHz) energy at a number of pulse widths and pulse repetition rates for varying lengths of time. The data was statistically analyzed to determine the 50-percent failure level for each stress condition. Curves are presented for the 50-percent failure level as function of the number of pulses applied for various pulse widths and as a function of pulse width for various numbers of pulses applied.

The analysis of the data is focused on the development of an empirical equation to predict diode failure as a function of various RF parameters. The failure criterion used and the reasons for this criterion are also discussed in Section II. A hypothetical system is postulated and a susceptibility analysis under an RF stress condition is performed in Section VI.

II. BACKGROUND AND OBJECTIVES

For several years, the Naval Weapons Laboratory has had an on-going program to investigate the effects of microwave radiation on solid state devices. One class of devices of particular interest is microwave diodes. These devices are nearly always located in the front ends of receiver systems in which they function as detectors of RF radiation. In such a location they are particularly subject to high power microwave radiation. Use of these diodes is such that a failure can render a system incapable of acquiring an intended RF signal. Considered in this report are X-band point-contact mixer diodes.

Point-contact diodes have been used in receiver systems for many years and much work has been done relative to their failure levels. The failure criterion used in most of the work has been a 3-dB change in noise figure. While this criterion may be suitable for diodes used in a laboratory system, it is of little use in naval electronics systems in which such a change may not seriously affect systems performance. In addition, until recently, pulse testing has always been done by the Torrey line method.[1*] In this method, a coaxial line is charged to some potential and then allowed to discharge through the diode. More recently, it has been accepted that this video pulse type test does not accurately simulate an RF pulse.[2,3]

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* Raised numerals refer to identically numbered items in the list of references at the end of text.

Manufacturers' burnout specifications have also been rather vague.[4] Burnout levels, based on video pulse tests and the 3-dB noise figure change criterion, do not give sufficient information to allow a detailed system susceptibility analysis. Exposure times are not definite, and failure levels given differ among manufacturers.

Failure levels are generally given for two conditions: continuous wave (CW) and short nanosecond video pulse exposure. Pulse widths greater than 0.1 microsecond are assumed equivalent to CW. In general, there is presently little failure information as a function of typical radar parameters, exposure times, or large changes in noise figure. This is the type of information required to evaluate an electronic system's susceptibility to radar environments.

The initial objective of this investigation was to determine the amount of noise figure degradation of 1N23 diodes as a function of typical radar parameters. Preliminary data, however, indicated that due to the diodes' response, this would not be possible. Figure 1 indicates this response. It is evident from this figure that the noise figure does not change monotonically, but rather undergoes random changes both increasing and decreasing, as a function of the number of pulses applied. This behavior is maintained until the change exceeds approximately 10 dB. Once the change in noise figure has exceeded 10 dB, the diode is permanently degraded and does not recover. It would therefore be prohibitive to predict, with any degree of confidence, noise figure changes of less than 10 dB for the application of a fixed number of pulses due to the random nature of these changes. The only meaningful change is one of greater than 10 dB. These results are in agreement with other test results.[5,6]

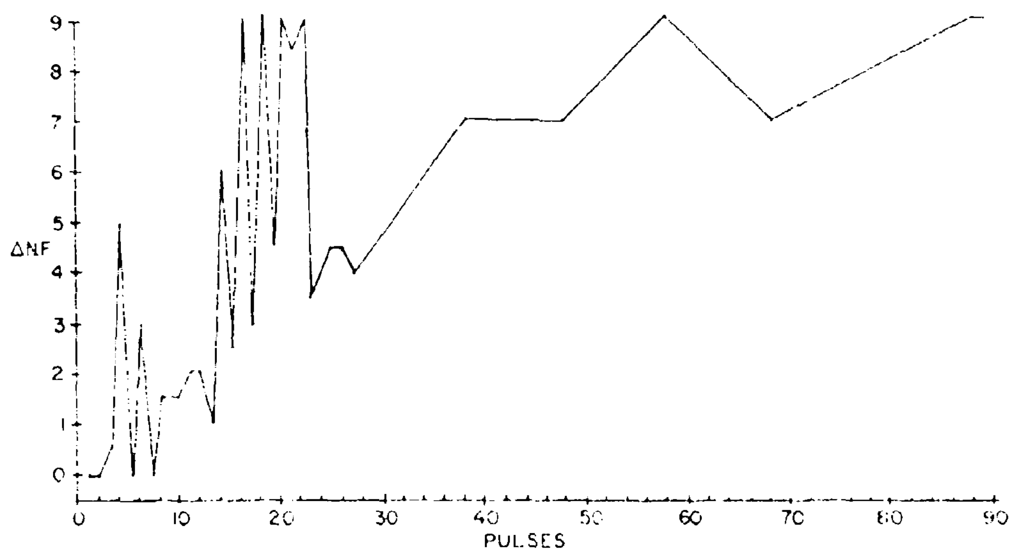

Figure 1. Change in Noise Figure vs Number of Pulses Applied 1N23 Diodes

In view of the above behavior, emphasis was placed on changes in noise figure of greater than 10 dB. This was done for various pulse widths, pulse repetition rates, and exposure times. Some work was also done on the amount of RF power reflected by the diodes as a function of incident power. Since the data has been corrected for reflections, the failure levels given are in terms of absorbed power. Information on the fractional amount of incident power reflected is therefore necessary in using the burnout data to perform system susceptibility analysis.

III. EXPERIMENTAL PROCEDURE

The basic apparatus used to expose the microwave diodes to RF is shown schematically in Figure 2. The RF source is a CW sweep generator used in the discrete frequency mode. Modulation was performed on the low level signal out of the oscillator and then amplified by the TWT. Pulse width and repetition rate were controlled by the pulse generator. A preselected number of pulses was achieved by use of the programmable data generator as a trigger source for the pulse generator, which was operated in the external trigger mode. The data generator was used in the manual recycle mode. The purpose of the one shot circuit was to actuate the data generator and the oscilloscope camera. The directional coupler sampled both the incident and reflected power. The outputs of the crystal detectors are replicas of the envelopes of the incident and reflected RF pulses. These signals were displayed on an oscilloscope and recorded photographically. The data required to compute the RF power dissipated by the diode under test was obtained from this photographic record. The response of the crystal detectors (i.e., RF power input vs video voltage output), combined with the calibration factors of the couplers and attenuators, provided the relation between displayed pulse amplititude (oscilloscope photo) and the incident and reflected power levels.

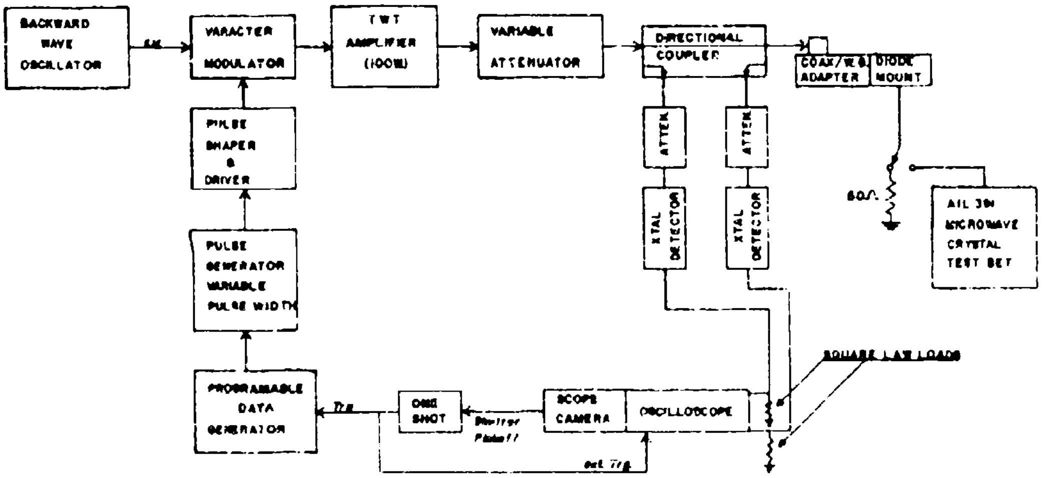

Figure 2. Schematic Diagram of Apparatus Used for RF Exposures

The RF source was operated at a frequency of 9.375 GHz. The pulse widths were varied from 0.3 μs to 100 μs. Variation in the pulse repetition rate was from 1 Hz to 10 kHz. The diodes were subjected to a fixed number of pulses ranging from 10 to 10K. The various conditions used for each test are given in Table 1.

Table 1. List of RF Parameters Used in Tests

Pulse Width (μs)	Repetition Rate (Hz)	No. of Pulses
1	1K	10
1	1K	100
1	1K	2K
1	1K	10K
1	400	10
1	1	10
1	10K	10
3	1K	10
3	1K	100
10	1K	10
10	1K	100
100	1K	10
0.3	1K	10
0.3	1K	100
0.3	1K	3.5K

The diode under test was placed in an untuned waveguide crystal mount and the video output of the diode was terminated in 50Ω. Since the RF impedance of the diode is matched to the waveguide impedance only at a power level of the order of 1 milliwatt, the incident and reflected powers were monitored to determine the net RF power dissipated by the diode. All failure levels reported are for net absorbed power.

Approximately 1000 diodes were tested. Each diode was placed in the crystal holder and the noise figure measured using the AIL Model 391 microwave crystal test set. This had been previously calibrated using an AIL Model 75 Precision Automatic Noise Figure Indicator. The diode was RF stressed and the noise figure was measured again. A record of the RF parameters (peak power, pulse width, number of pulses) and noise figure change was made for each diode tested. Each diode was stressed only once to prevent cumulative effects from distorting the data.

IV. DATA ANALYSIS

A statistical analysis of the data was performed to determine percent failure as a function of absorbed power. For each set of RF parameters listed in Table 1, a number of diodes was tested at each of several input power levels. Due to slight variations in incident input power and differences in the amount of power reflected for each diode, the data for each test condition exhibited a wide range in absorbed power levels. For each test condition, the diodes were arranged in groups. These groups were defined in such a way that all diodes whose absorbed power fell within a specified range were considered as being in one cell. The cell widths were chosen so that a minimum of 20 diodes would be contained in each cell. The range of absorbed power in each cell was no more than ± 10 percent about the average value.

As an example, data analysis of the diodes tested at 1-kHz pulse repetition rate, 1-μs pulse width, and an exposure of 10 pulses follows. Four cells were defined for this case. All diodes whose absorbed power fell within the limits 47 to 55 watts, 40 to 45 watts, 33 to 38 watts, and 26 to 29 watts were grouped in their respective cells. The average absorbed power for each cell was 52 watts, 42 watts, 35 watts, and 27 watts, respectively. Of the total devices tested in each cell, the percent failed was calculated. This yielded the following results:

Cell Width (watts)	Average Absorbed Power Value (watts)	Percent Failed
47-55	52	92
40-45	42	62
33-38	35	50
26-29	27.3	33.3

Figure 3 is a graph of this data. Five-percent error bars were used as being a reasonable maximum experimental error.

The procedure outlined above was followed for all test conditions listed in Table 1 except for those diodes tested at 0.3 μs. For this case, only the 50-percent failure level was determined. Figures 4 through 12 are graphs for the remaining test conditions.

The data was also analyzed to determine the percentage of the power reflected as a function of incident power. The incident power was divided into cells 1 watts wide starting at 0 watt. For each incident power data point, the percent reflected was determined. The average incident power and percent reflected were calculated for each cell and are presented in Figure 13. The error bars are determined from the standard deviation. This curve is valid only for systems in which the diode is tuned to absorb 100 percent of the incident power at an input of 1 mW. This is not a serious drawback since it is typical of most diode mixers.

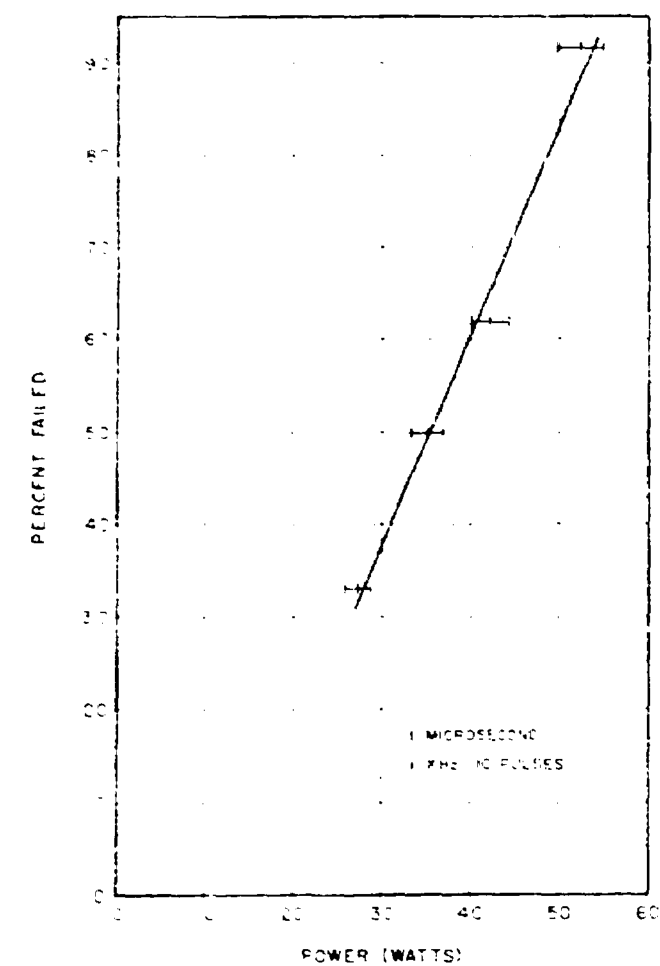

Figure 3. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 1-kHz PRF, 10 Pulses

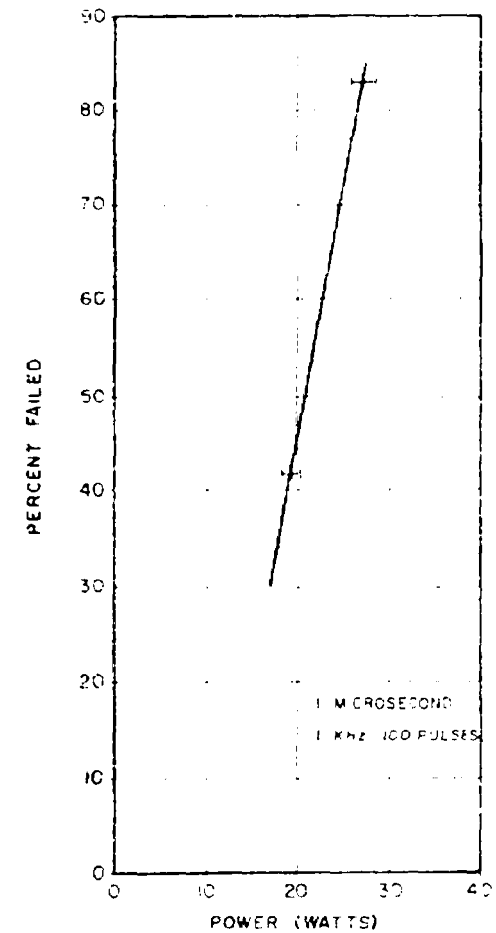

Figure 4. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 1-kHz PRF, 100 Pulses

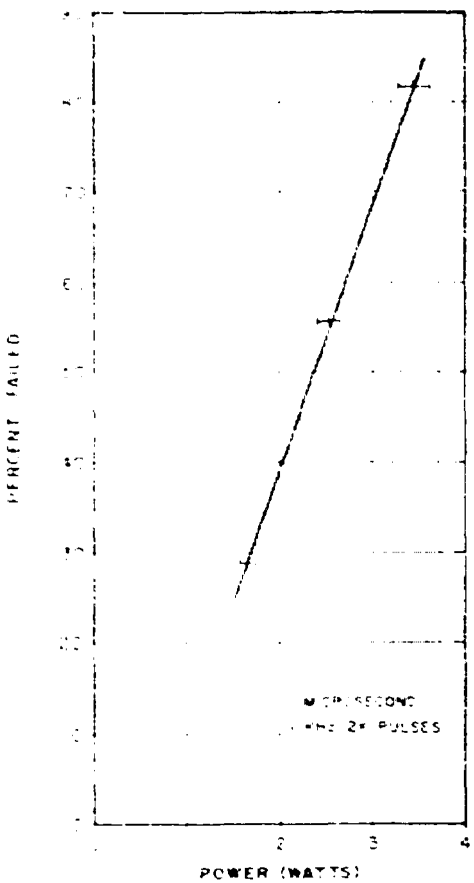

Figure 5. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 1-kHz PRF, 2K Pulses

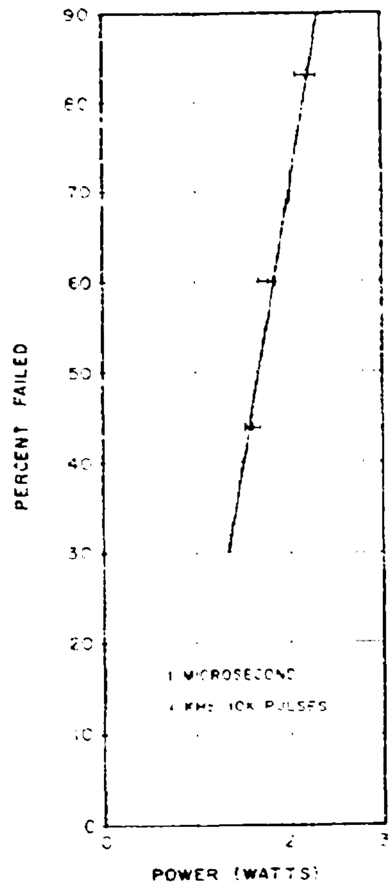

Figure 6. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 1-kHz PRF, 10 K Pulses

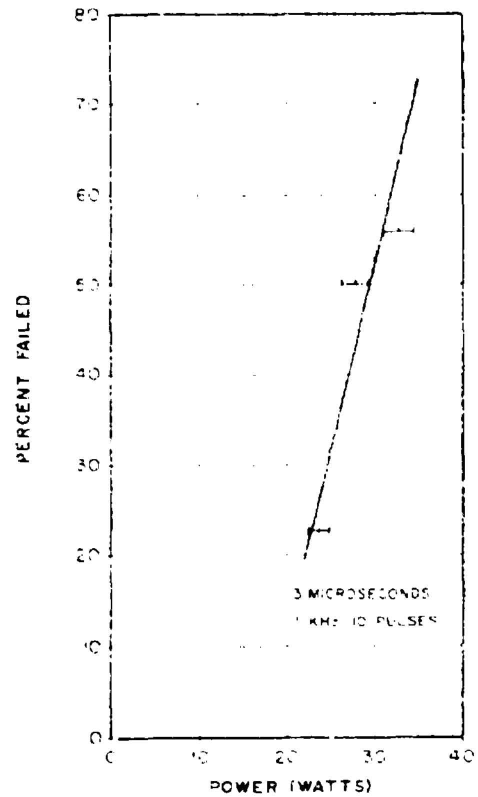

Figure 7. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 3-μs Pulse Width, 1-kHz PRF, 10 Pulses

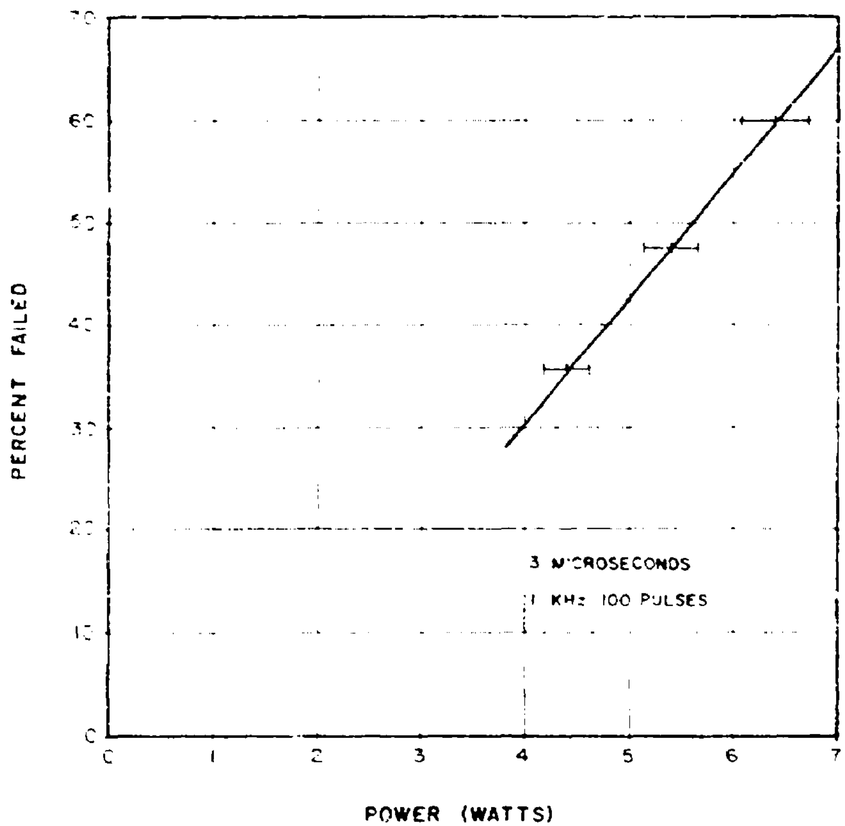

Figure 8. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 3-μs Pulse Width, 1-kHz PRF, 100 Pulses.

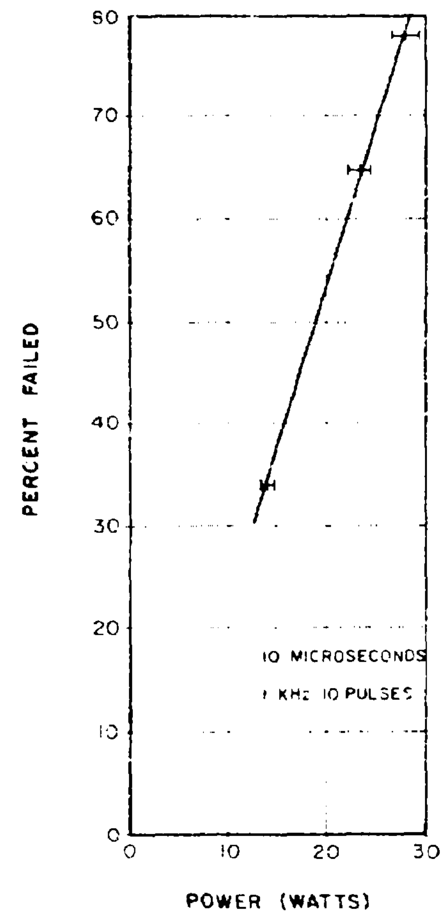

Figure 9. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 10-μs Pulse Width, 1-kHz PRF, 10 Pulses.

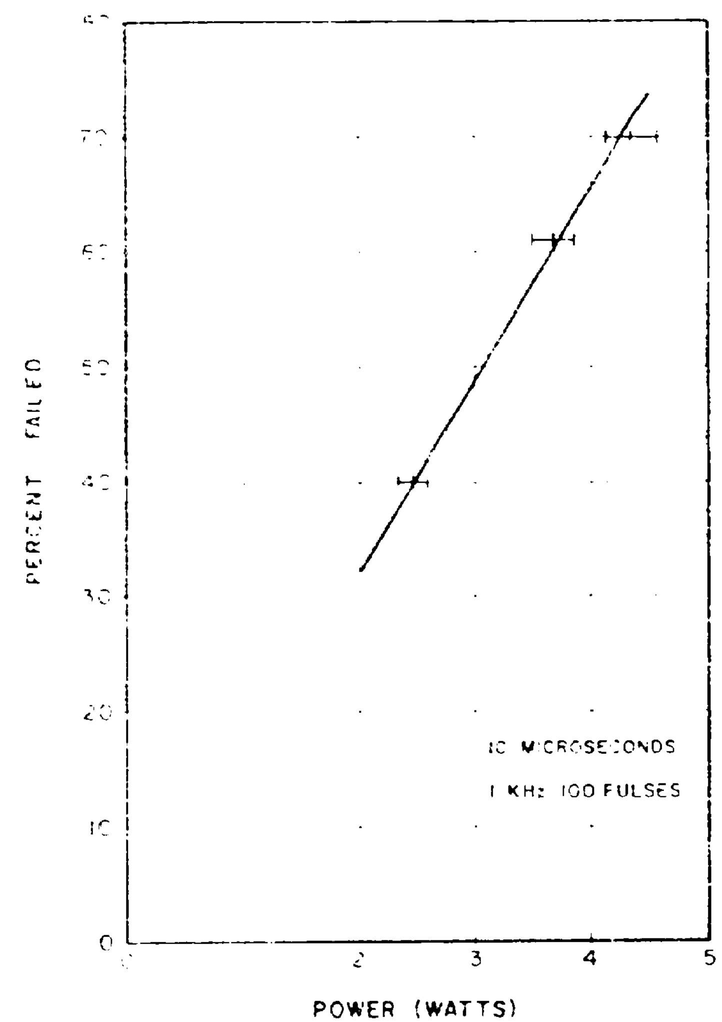

Figure 10. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 10-μs Pulse Width, 1-kHz PRF, 100 Pulses

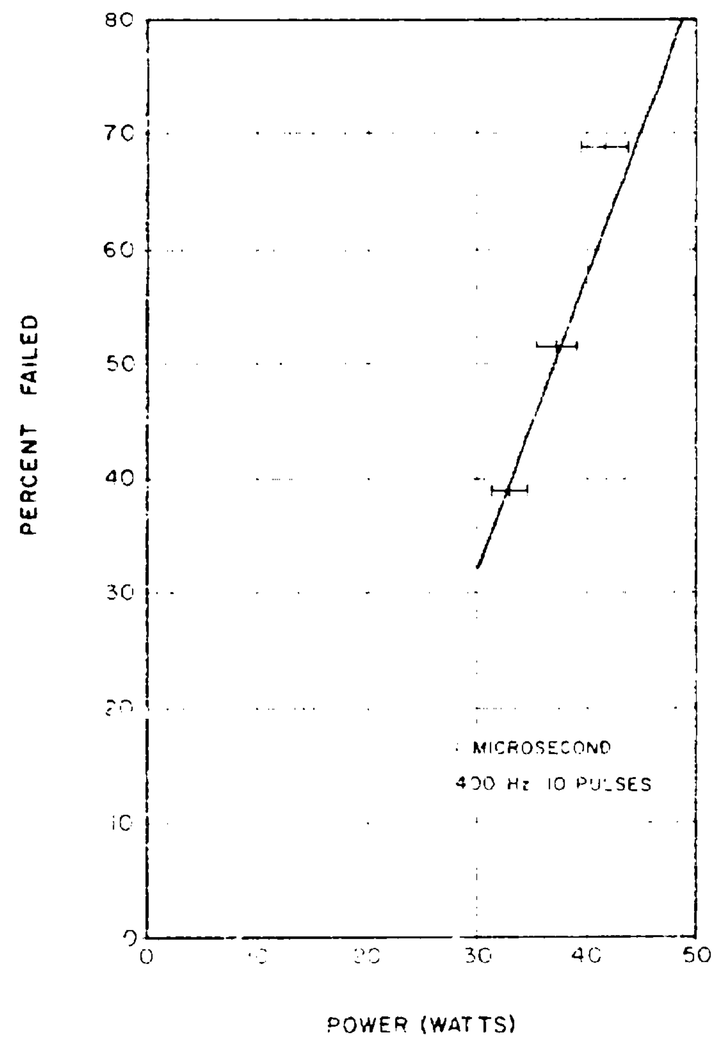

Figure 11. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 400-Hz PRF, 10 Pulses

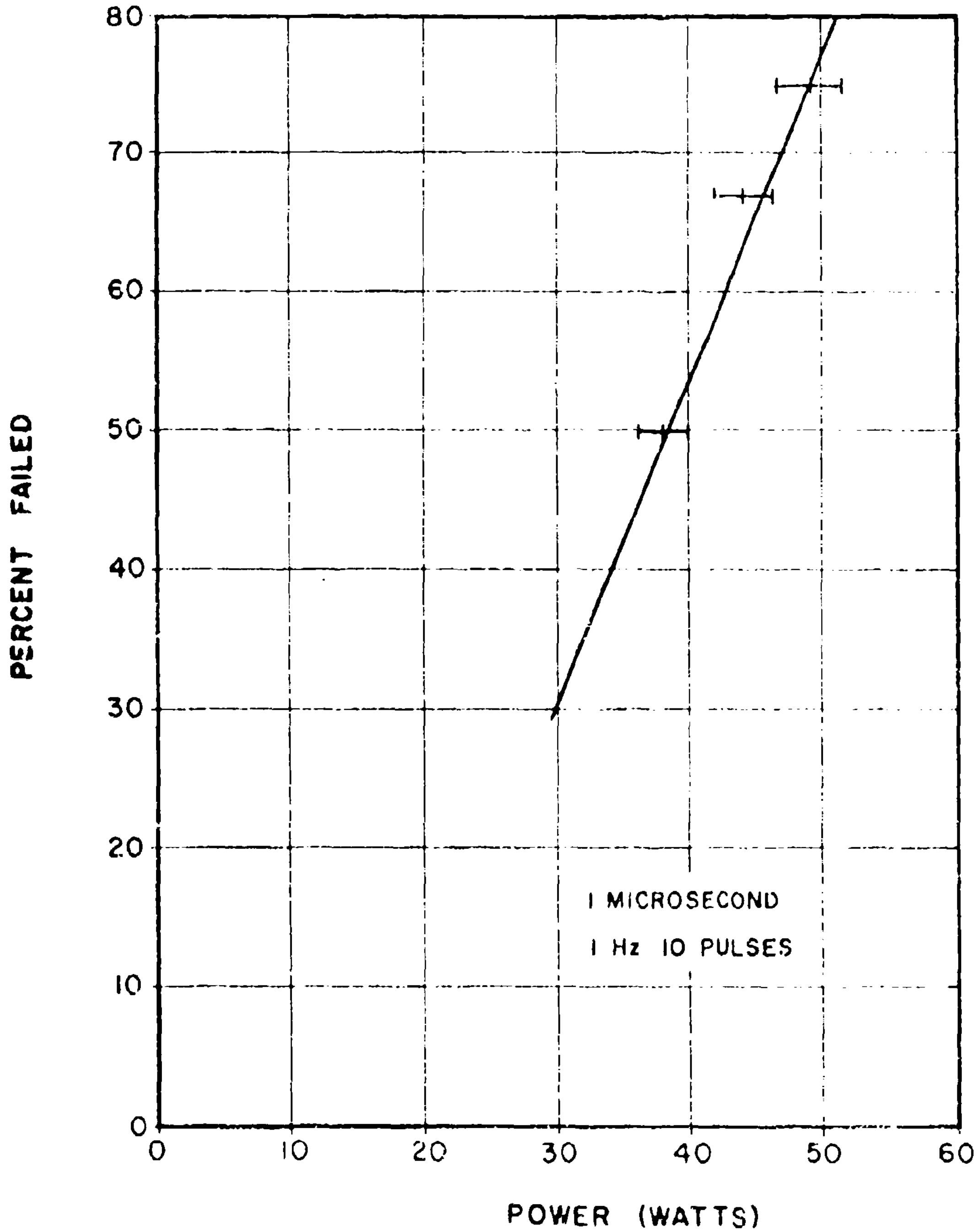

Figure 12. Percent Failure Levels of 1N23 Diodes as a Function of Peak Absorbed Power for Exposure Conditions: 1-μs Pulse Width, 1-Hz PRF, 10 Pulses

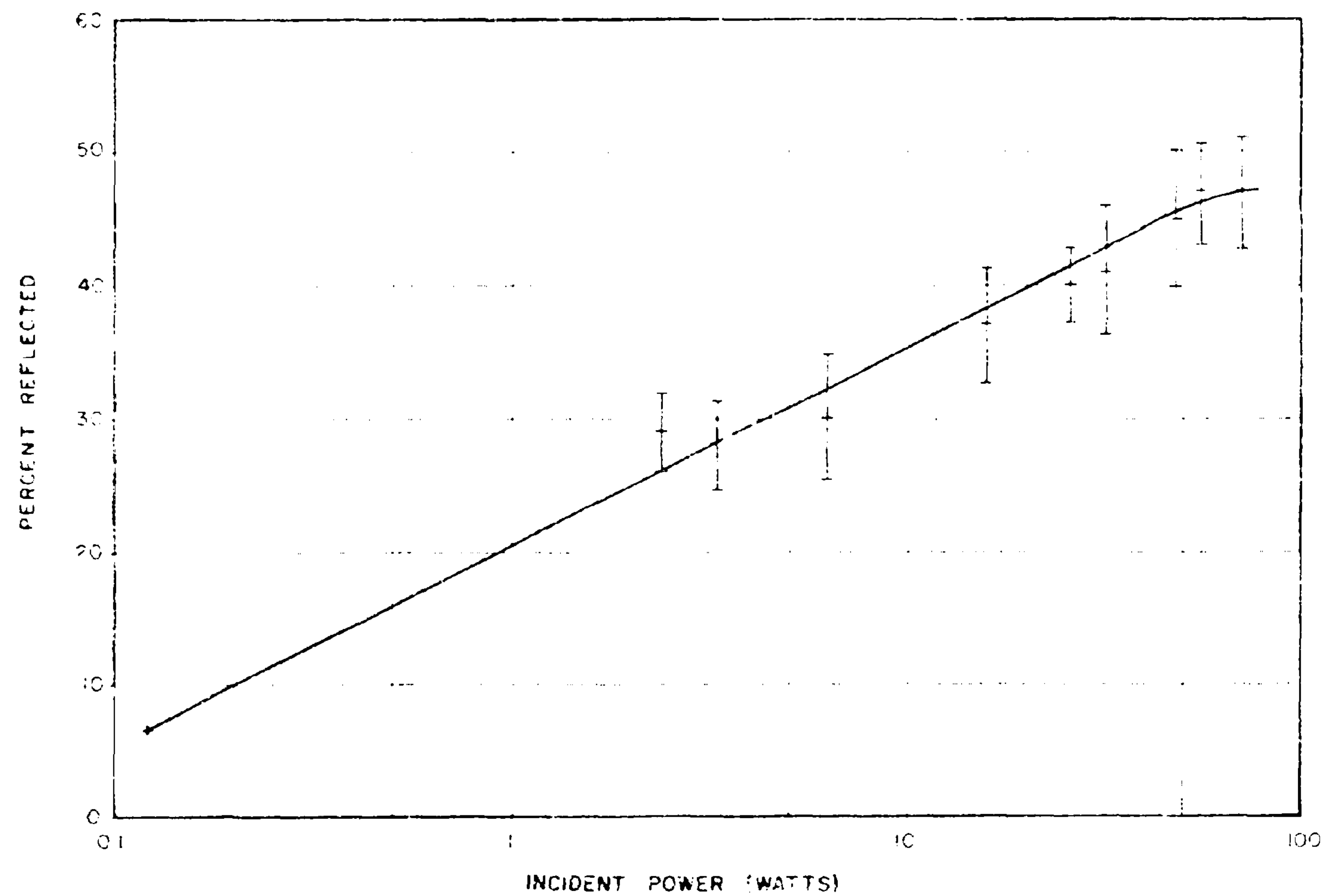

Figure 13. Percent of Power Reflected vs Incident Power for 1N23 Diodes

V. RESULTS

One significant result which was determined is presented in Figure 14. This is a plot of the 50-percent failure level as a function of pulse repetition rate for a 1-μs pulse width and a stress of 10 pulses. It is clear from the graph that the failure level is essentially independent of pulse repetition rate up to at least 10 kHz. This behavior indicates a thermal relaxation time for the diode which is much faster than 100 μs, which is reasonable.

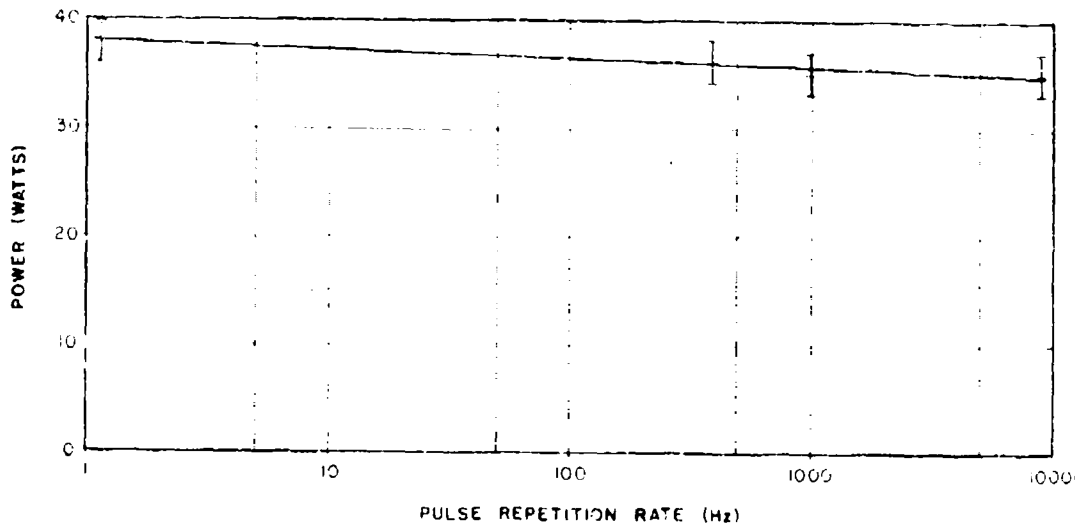

Figure 14. Peak Absorbed Power Required for 1N23 Diode 50-Percent Failure Level vs Pulse Repetition Rate for 1-μs Pulse Width

Figures 15 and 16 are the results of the analysis for the 50-percent failure level. Figure 15 is a plot of the 50-percent failure level as a function of pulse width for various numbers of applied pulses. It can be seen that for very long pulse widths, all the curves tend toward a CW failure level, as expected. Figure 16 is a plot of the 50-percent failure level as a function of the number of applied pulses. The 0.1-μs curve was obtained by extrapolating the curves of Figure 15. Due to their linear behavior in that region, this seems reasonable. Although the curves are plotted down to exposures of 10 pulses, their linear behavior should allow one to extend these down to a single pulse exposure. For a large number of applied pulses, these curves also tend toward a CW level. Since the 50-percent failure level is independent of pulse repetition rates up to 10 kHz, the number of pulses required to cause failure can be transformed into exposure time for a given repetition.

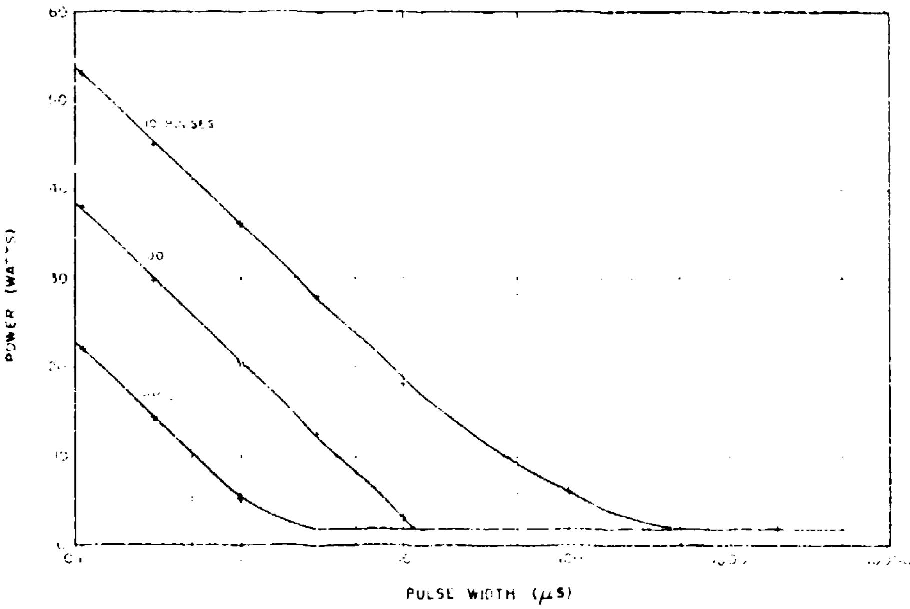

Figure 15. Peak Absorbed Power for 1N23 Diode 50-Percent Failure Level vs Pulse Width for Various Numbers of Applied Pulses

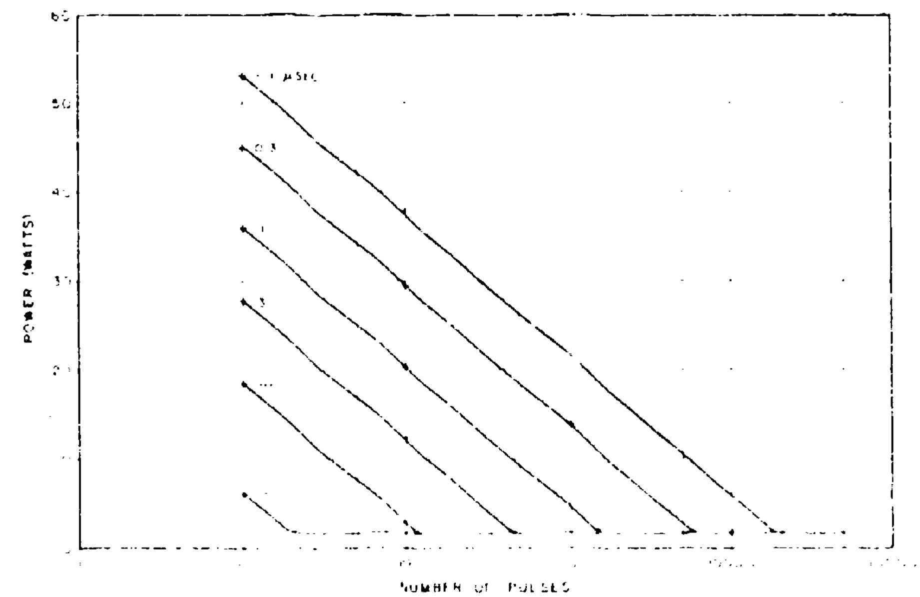

Figure 16. Peak Absorbed Power for 1N23 Diode 50-Percent Failure Level vs Number of Applied Pulses for Various Pulse Widths

Figure 16 is particularly interesting in that all the curves tend to have the same slope. It can be seen, for example, that the failure for a 1-μs, 10-pulse stress condition is approximately the same as the failure level for a 0.1-μs, 100-pulse stress condition. This relation is more clearly indicated in Figure 17 where the 50-percent failure level is plotted as a function of the product of the pulse width and number of applied pulses. The straight line drawn through the data points was determined as a least squares fit to the data and is given by the empirical formula on the graph. For any given pulse repetition rate up to 10 kHz and pulse width greater than 0.1 μs, the 50-percent failure level can be determined by the use of the empirical expressions given in Figure 17.

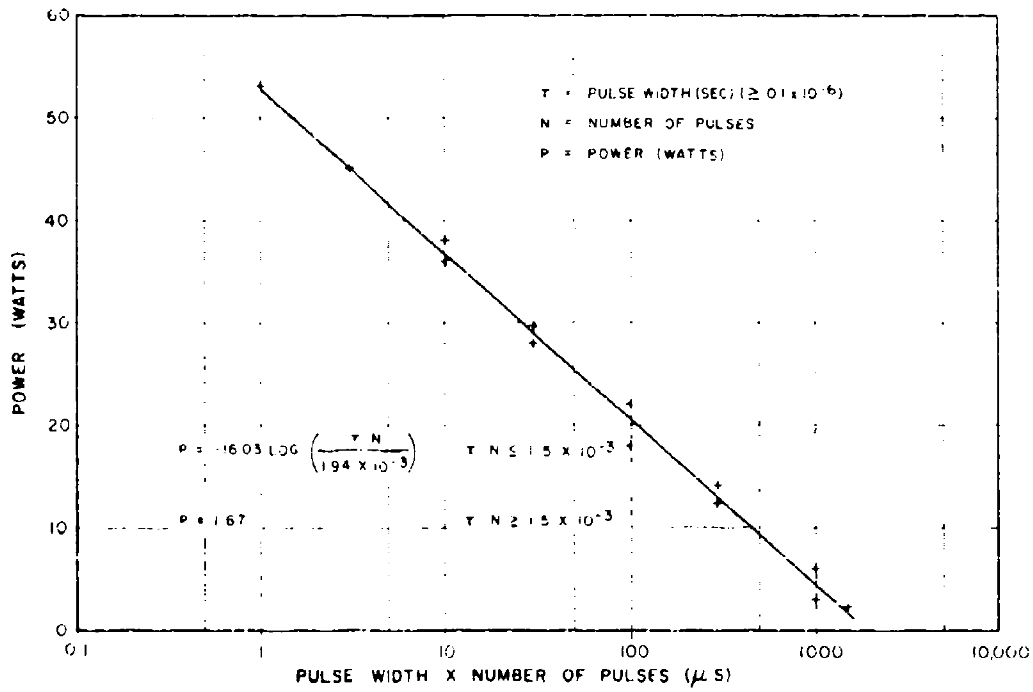

Figure 17. Experimental 50 Percent Failure Levels of 1N23 Diodes as a Function of the Product of the Pulse Width and Number of Pulses Applied (The line drawn is a best fit to the data points as given by the above empirical equation.)

VI. DATA UTILIZATION

The data given in this report can be used to evaluate the survivability of naval electronic systems in typical radar environments when such systems employ microwave diodes. This can be done either in the design phase, to ensure sufficient protection, or on existing equipment, to determine vulnerability. A sample problem will serve to demonstrate this utilization.

Assume one is concerned with the possible vulnerability of a receiver which is carried aboard ship. The characteristics of the receiver are as follows:

Antenna gain:	16 dB
Operating frequency:	X-band
Diode holder:	Balanced mixer

As a possible radar threat aboard ship, assume the following operational characteristics:

Power output:	200 kW
Pulse width:	0.8 μs
Pulse repetition rate:	1200 Hz
Frequency:	9600 MHz
Antenna gain:	36 dB

It is possible for the receiver to be exposed to the radar at a distance of 50 m for 50 ms. The equations needed to analyze this problem are as follows:

$$P_R = \frac{(P_T G_T A_R)}{4\pi R^2}(1-L)\,M \tag{1}$$

$$P_A = P_R(1-F) \tag{2}$$

$$P_F = 46.03 \, \mathrm{LOG} \, \frac{(T/N)}{(1.91 \times 10^{-3})} \tag{3}$$

where,

P_R = Power (peak) reaching diode in watts

P_T = Power (peak) transmitted by threat radar in watts

G_T = Threat radar antenna gain

A_R = Receiver antenna effective area

L = Fractional losses between receiver antenna and mixer

M = A number determined by the mixer characteristics

P_A = Power (peak) absorbed by diode in watts

F = Fractional power reflected by diode

P_F = 50-percent power failure level

T = Pulse width in seconds

N = Number of pulses

For this case, assume there are no losses between the receiving antenna and the mixer. Since the mixer is a balanced mixer containing two diodes each of which receives half of the power incident upon the mixer, F is 0.5. Then the power reaching the diode at a distance of 50 m is calculated to be about 40 watts. From Figure 13 and equation (2), the power absorbed by the diode is about 26 watts.

Under the assumed condition of a 50-ms exposure, 60 pulses will be received. Using equation (3), the failure level for these conditions is about 26 watts. In this case, the receiver vulnerability is marginal. If this were to be a receiver in a new system, the analysis indicates that some protection should be built into the receiver to ensure survivability in the anticipated environment.

VII. CONCLUSIONS

The results of measurements on 1N23 X-band point-contact microwave diodes using a noise figure change of 10 dB or greater as the failure criterion, permit the following conclusions to be drawn:

1. Meaningful data can be obtained by a measurement of the percent of a sample population of diodes which fail when stressed at some particular power level, pulse width, pulse repetition rate (PRR), and number of pulses (exposure time).

2. For a given pulse width and number of pulses, the failure level is essentially independent of the pulse repetition rate for PRRs up to at least 10 kHz.

3. For pulse widths $\geq$ 0.1 μs, the failure level varies as the logarithm of the product of pulse width and the number of pulses in the exposure.

4. For the full range of pulse widths studied, the pulsed failure levels approach the CW failure levels for large numbers of pulses, as predicted.

5. For any pulse repetition rate $\leq$ 10 kHz and pulse width $\geq$ 0.1 μs, the power level at which 50 percent of a sample population of diodes will fail from exposure

to a specified number of pulses can be determined by using the empirically derived expression in Section V.

In addition, for the reasons set forth in Section II, it is not meaningful to employ a change in noise figure of less than 10 dB as a failure criterion for exposures to a fixed number of pulses.

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